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# Test of Structure Functions Using Lepton Pairs: W-Charge Asymmetry and Drell-Yan Production at CDF

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# TEST OF STRUCTURE FUNCTIONS USING LEPTON PAIRS: W-CHARGE ASYMMETRY AND DRELL-YAN PRODUCTION AT CDF

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The charge asymmetry of leptons from $W$-bosons and the Drell-Yan cross section of massive charged lepton pairs from $\gamma^*/Z$-bosons produced in $p\bar{p}$ collisions are measured using 110 pb$^{-1}$ of collisions taken by the Collider Detector at Fermilab (CDF) during 1992-95. The $W$-asymmetry measurement provides a precise constraint of the slope of the quark distribution ratio, $d(x)/u(x)$, over the $x$ range of 0.006 to 0.34. The Drell-Yan measurement spans the mass range of 11 to 500 GeV/$c^2$, and QCD calculations using recent parton distribution functions are in good agreement with it.

## 1   Introduction

In hadron-hadron collisions, massive lepton pairs are produced via the Drell-Yan [1] process. At the Tevatron collider, the hadron-hadron collisions are symmetric $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. In the standard model, quarks and anti-quarks annihilate into $W$ or $\gamma^*/Z$ bosons, which then decay into lepton pairs:

$$q + \bar{q}' \to W \to l + \nu \qquad (1)$$
$$\to \gamma^*/Z \to l^+ + l^- \ .$$

Since the $p$ and $\bar{p}$ provide the flux of colliding quarks, the Drell-Yan process provides information on the proton's parton distribution functions (PDFs). The leading order quantum chromodynamics (LO QCD) cross section is

$$\frac{d^2\sigma}{dM^2 dy} = \sum_{q,q'} x_p x_{\bar{p}} \left[ q(x_p)\bar{q}'(x_{\bar{p}}) + (p \leftrightarrow \bar{p}) \right] \hat{\sigma}_{q,q'}, \quad (2)$$

where the sum is over the annihilating quarks, the $x$'s are the quark momentum fractions, $q$ ($\bar{q}$) is a quark (antiquark) PDF of the proton, $y = 0.5 \ln x_p/x_{\bar{p}}$ and $M^2 = x_p x_{\bar{p}} s$ are the rapidity and mass squared of the lepton pair, and $\hat{\sigma}_{q,q'}$ is the parton level cross section. The Drell-Yan processes are $s$-channel analogs of the deep inelastic scattering (DIS) processes. Since the QCD interactions for the Drell-Yan process are in the initial state only, the theoretical calculations are robust. Thus, dilepton production at the Tevatron can be used both to test the accuracy of QCD and to obtain information on PDFs in conjunction with DIS. There are no nuclear target effects, and nonperturbative effects are minimal due to the large $Q^2$ scale: $M_W^2$ or $M_{\gamma^*/Z}^2$.

In this study, dileptons from $W \to e\nu, \mu\nu$ and $\gamma^*/Z \to e^+e^-, \mu^+\mu^-$ in 110 pb$^{-1}$ of collisions recorded by CDF during 1992-95 are utilized. The CDF detector [2] is shown in Fig. 1. The leptons are reconstructed and identified using charged particle trackers ($|\eta| < 2.4$) in the 1.4 T axial magnetic field, electromagnetic and
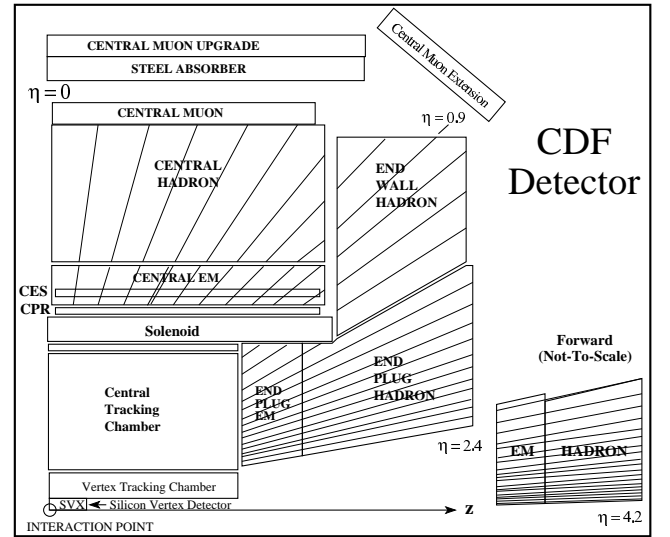


Figure 1: A quarter section view of the CDF detector.

hadronic calorimeters ($|\eta| < 2.4$), and muon detectors. Both the central ($|\eta| < 1$) and forward ($1.9 < |\eta| < 3.5$) (not shown in Fig. 1) muon detectors are used.

## 2   W Asymmetry

At the Tevatron, $W^+$ and $W^-$ bosons are produced asymmetrically in $y$. $W^+$ ($W^-$) bosons are primarily from annihilations of $u$ ($d$) quarks from $p$'s and $\bar{d}$ ($\bar{u}$) from the $\bar{p}$'s. In LO QCD, $\sim$85% of the $W$'s are from these collisions. As a $u$ quark carries more of the proton's momentum than a $d$ quark [3,4,5], $W^+$'s tend to be boosted along the proton direction ($y > 0$), and $W^-$'s the other way around. The $W^+$ to $W^-$ production asymmetry in the boson rapidity

$$\mathcal{A}(y) \equiv \frac{d\sigma^+/dy - d\sigma^-/dy}{d\sigma^+/dy + d\sigma^-/dy} \simeq \frac{d/u(x_{\bar{p}}) - d/u(x_p)}{d/u(x_{\bar{p}}) + d/u(x_p)} \quad (3)$$

measures the slope of the $d$:$u$ quark PDF ratio [6,7].

The asymmetry, $\mathcal{A}(y)$, cannot be directly measured at the Tevatron because the neutrino momentum in the $W \to e\nu, \mu\nu$ decay is unconstrained. Instead, the charge asymmetry of the decay $e$'s and $\mu$'s

$$A(y_l) = \frac{dN_+(y_l) - dN_-(y_l)}{dN_+(y_l) + dN_-(y_l)} \qquad (4)$$

is measured. The $N_\pm$ are the observed numbers of $l^\pm$ as a function of the lepton pseudorapidity, $y_l$. The asymmetry is a convolution of the $W$ production asymmetry and the well understood $V - A$ decay of the $W$'s. The range of the measurement is $|y_l| < 2.4$ $(0.006 < x < 0.34)$. As $A(y_l)$ is a ratio, many experimental systematic uncertainties cancel: acceptances, efficiencies, and the luminosity. Theoretical cross section normalization uncertainties also cancel out in calculations.

The leptons in different detectors are analyzed separately and combined at the end for $A(y_l)$. There are central electrons ($|y_l| < 1.1$), plug electrons ($1.1 < |y_l| < 2.4$) inside the silicon vertex detector (SVX) fiducial region, plug electrons ($1.1 < |y_l| < 2.4$) outside the SVX fiducial region, central muons ($|y_l| < 1$), and forward muons ($1.9 < |y_l| < 2.5$). Since $A(y_l)$ is a charge asymmetry, a reliable charge determination for the leptons is essential. Central electrons, central muons, and plug electrons outside the SVX fiducial region are required to have a track in the central tracking chamber (CTC) with a well determined charge. The charge of forward muons is well measured by the separate forward muon spectrometer (FMU). To reduce backgrounds, only the region of the FMU that shadows the plug calorimeter is used.

In the plug region, the SVX is used to extend tracking[8] to $|\eta| = 2.4$ of the plug electromagnetic calorimeter (PEM). Consider an electron going through the SVX, bending in the axial magnetic field, entering the PEM, and then showering. The SVX provides the azimuthal direction at the vertex. The PEM provides the final azimuthal direction after the bend; this give the charge. The PEM also provides the electron's energy (momentum), which is correlated with the bend angle. Any unrelated SVX track and PEM showers are eliminated with this correlation. This new charge determination method doubles the acceptance of plug electrons.

The $W \to l\nu$ events are selected by requiring the transverse energy $(E_T)$ of the $e, \mu$ candidates be larger than 25 GeV. The presence of the $\nu$ is accounted by requiring the missing $E_T$ of the event to be larger than 25 GeV. To reduce QCD backgrounds, jets in the event are required to have $E_T < 30$ GeV. The $e$ and $\mu$ candidates are required to pass identification cuts, to be isolated from other activity in the calorimeters, and to be well tracked.

Measurement systematics of $A(y_l)$ are minimal. The asymmetry of leptons in different detector systems are
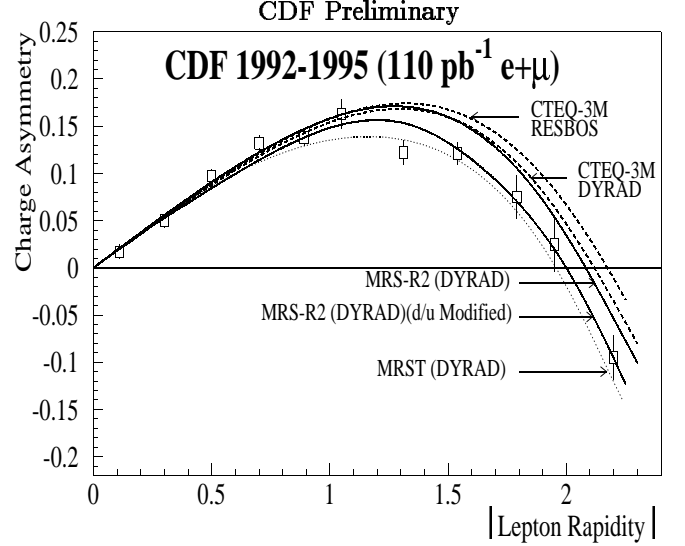


Figure 2: The lepton charge asymmetry, $A(y_l)$. The asymmetry is fully corrected. The errors are the statistical and systematic errors added in quadrature. The curves are theoretical predictions discussed in the text.

consistent with each other. There are no charge dependent biases in the acceptances or efficiencies. Therefore, the acceptances and efficiencies cancel out in $A(y_l)$. The charge misidentification rate is small; it ranges from 0.2% at $|y_l| = 0$ to 10% at $|y_l| = 2.2$. The backgrounds are found to be small. The $W \to \tau\nu$ background is $\sim 2\%$ in all regions. The dijet background is under 1% in the central region, $\sim 2\%$ for plug electrons, and $\sim 4\%$ for the forward muons. The $Z \to ee, \mu\mu$ (where an $e$ or $\mu$ is lost in a detector crack) backgrounds are: negligible for electrons and 5-6% for the muons. Backgrounds from $Z \to \tau\tau$ are negligible. The signal dilution from charge misidentification and backgrounds are corrected.

For the final $A(y_l)$, the measurements from leptons in different detector systems are combined. By CP invariance, $A(y_l)$ is asymmetric, and the $-y_l$ points are combined with the $+y_l$ ones. The fully corrected $A(y_l)$[9] shown in Fig. 2 is for leptons (including the neutrino) with $E_T > 25$ GeV. This can be compared directly with theory. The asymmetry depends not only on the $d{:}u$ quark PDF ratio, but also on the $W$ boson transverse momentum $(P_T)$ distribution because of the lepton $E_T$ cuts. The curves in Fig. 2 gives QCD predictions with different PDF parameterizations and $W$ boson $P_T$ distributions. The DYRAD[10] curves use next-to-leading-order (NLO) calculations. The RESBOS[11] curve uses a NLO calculation and also resums soft gluon emissions to all orders. Fixed order NLO QCD calculations such as DYRAD do not reproduce the $W$-$P_T$ distribution. The $W$-$P_T$ distribution is more accurately described by gluon resum-

mation calculations. The CTEQ-3M [4] and MRS-R2 [12] global PDF fits include a previous CDF measurement [13] of $A(y_l)$ extracted from data recorded in 1992-93 (20% of the data reported here). In the $|y_l| < 1$ region, the agreement is good. At larger rapidities, both the RES-BOS calculation using CTEQ-3M and the DYRAD calculations using CTEQ-3M and MRS-R2 are larger than the measurement. The new measurement and these calculations are consistent with the previous measurement because that measurement has large errors in the $|y_l| > 1$ region. The differences between the $A(y_l)$ measurement and calculations in the $|y_l| > 1$ region suggests there may be problems with the PDF $d(x)/u(x)$ ratios. The new measurement has been incorporated into the MRST [14] PDFs. The DYRAD calculation using the MRST PDFs has improved agreement. Recently, the NMC data on muon scattering on hydrogen and deuterium have been reanalyzed [15] using improved corrections for nuclear binding effects in the deuteron. To account for these effects in PDFs, the $d/u$ ratio needs a correction of the form, $\Delta(d/u) = 0.1x(1 + x)$. The asymmetry, calculated with DYRAD and the MRS-R2 PDFs modified with $\Delta(d/u)$ is also shown in Fig. 2. It agrees quite well with the new measurement.

## 3 Drell-Yan Production

In this section, Drell-Yan production refers to lepton pair production via $\gamma^*/Z \to e^+e^-, \mu^+\mu^-$. Unlike $W^\pm$ production, the $\gamma^*/Z$ bosons are produced symmetrically in $y$. CDF measures the cross section, $d^2\sigma/dMdy(|y| < 1)$, which is an average of $d^2\sigma/dMdy$ over the somewhat flat, central plateau region of $|y| < 1$. The $M$ and $y$ are the mass and rapidity of the lepton pair (or equivalently, the $\gamma^*/Z$ boson). QCD calculations for this process are in good shape so this cross section measurement can be used to test the consistency of QCD$\oplus$PDF predictions.

Experimentally, the process is distinctive: there are two charged $e$'s (or $\mu$'s) in an event and they tend to be well separated from jets of hadrons and other particles from the collision. The kinematics ($M$ and $y$) can be fully reconstructed from the measured properties of the leptons. However, the absolute normalization of the cross section is difficult because the measurement of the $p\bar{p}$ luminosity at the Tevatron is complex. The luminosity error for the bulk of the data is presently ∼8%. There are two separate measurements: a high mass and high lepton $E_T$ cross section covering $M > 40$ GeV/c$^2$, and a low mass and low lepton $E_T$ cross section covering $M < 150$ GeV/c$^2$. Together, these measurements span $11 < M < 500$ GeV/c$^2$ ($0.006 < x < 0.28$).

The leptons selected are contained within the central ($|\eta| < 1$) detectors. The $e$ and $\mu$ candidates are required to pass identification cuts, to be isolated from
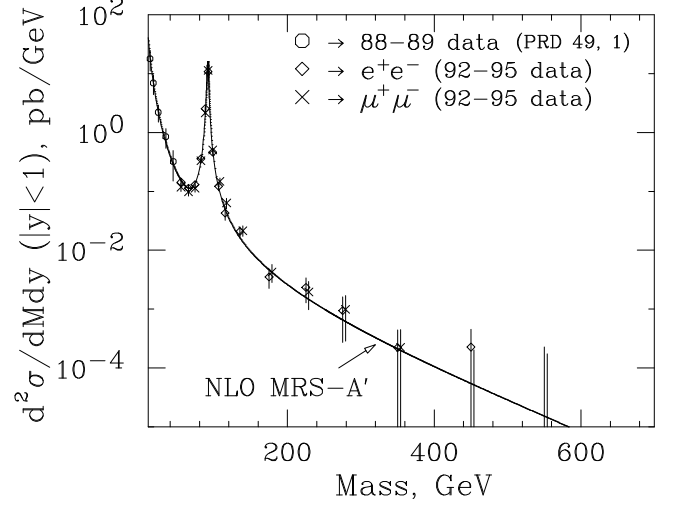


Figure 3: The high mass $d^2\sigma/dMdy$ ($|y| < 1$) measurement. The circles ($M < 50$ GeV) are from an earlier [17] measurement. The data are normalized from 50 to 150 GeV to the NLO QCD calculation. Above 110 GeV, the data symbols are displaced for clarity.

other activity in the calorimeters, and to be well tracked in the CTC. Candidate $ee$ and $\mu\mu$ pairs are required to be oppositely charged.

For the high mass/$E_T$ measurement [16], the electrons have $E_T > 20$ GeV and $|y_l| < 1$. For the selected high mass $\mu\mu$ pairs, one muon has $P_T > 20$ GeV/c, a matching track in a $|\eta| < 0.6$ central muon detector; the other muon has $P_T > 17$ GeV/c and $|y_l| < 1.2$. The $P_T > 17$ GeV/c muon need not have a track in a central muon detector, but it must have minimum ionizing signals in the calorimeters. Cosmic ray muons are removed using tracking and calorimeter timing cuts. The sample is nearly background free. The remaining cosmic ray backgrounds are negligible. Charge symmetric backgrounds from jets are estimated using same-charge lepton pairs, and the level is under 0.2%. Mostly oppositely charged backgrounds from $W^+W^-$, $\tau^+\tau^-$, $c\bar{c}$, $b\bar{b}$ and $t\bar{t}$ are estimated using $e\mu$ pairs, and the level is under 0.7%. These backgrounds are removed. Figure 3 shows the measured cross section and a NLO QCD calculation [18] using MRS-A' [19] PDFs. The calculation using CTEQ-3M PDFs is indistinguishable from the one using MRS-A' PDFs in Fig. 3. The data are normalized over $50 < M < 150$ GeV/c$^2$ range to take out absolute normalization differences. There is good agreement between the shape of the measurement and the calculation over the entire mass range.

For the low mass/$E_T$ measurement, the $E_T$ cuts are much lower. One of the leptons in the pair has $P_T > 8$ GeV/c and the other has $P_T > 4$ GeV/c. The electrons are required to have $|y_l| < 1$. For selected $\mu\mu$ pairs, the $P_T > 8$ GeV/c muon has a matching

**CDF Preliminary**

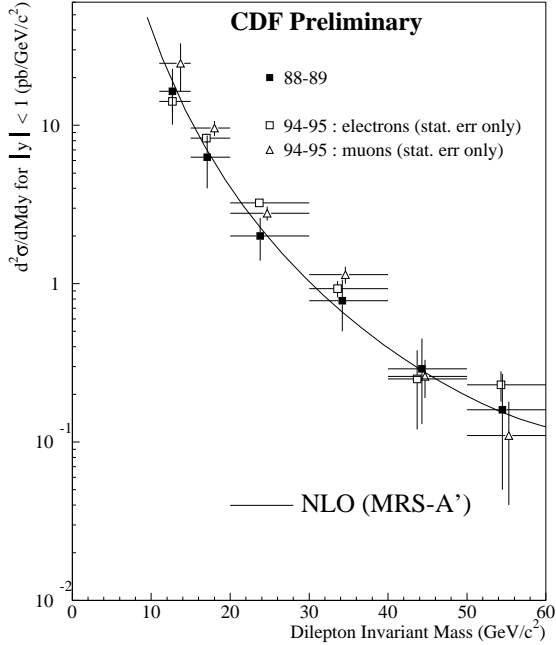Figure 4: The low mass $d^2\sigma/dMdy$ ($|y| < 1$) measurement. The data points are slightly displaced for clarity.

track in the $|\eta| < 0.6$ central muon detectors, and the $P_T > 4$ GeV/c muon has a matching track in one of the $|\eta| < 1$ central muon detectors. Cosmic ray muons are removed. The data sample is not the same as the one in the high mass analysis. The data is from $\sim 90$ pb$^{-1}$ of collisions from the 1994-95 run, and the events are from a prescaled, lower $P_T$ trigger sample. Due to the much lower $E_T$ cuts, the final sample has significant backgrounds. The backgrounds are determined using same-charge $ee/\mu\mu$ pairs and $e\mu$ pairs from the sample. These backgrounds are removed. The low mass analysis is ongoing, and the preliminary results in the $M < 60$ GeV/c$^2$ region are shown in Fig. 4. The new $ee$ and $\mu\mu$ cross sections are consistent with each other and the previous, 88-89 measurement [17]. The new measurement has $\sim 20$ times the data as the previous one. The curve in the figure is the same NLO QCD calculation shown in Fig. 3. The QCD calculation is also consistent with the data.

## 4 Summary

The $W$-charge asymmetry measurement provides a precision test of the slope of the $d/u$ quark PDF ratio over the quark momentum fraction range of $0.006 < x < 0.034$ at $Q^2 \sim M_W^2$. The measurement indicates parton distribution functions need to be updated to accomodate the $|y_l| < 1$ data. This illustrates the value of collider data in the measurement of parton distribution functions. The small errors of this $W$-charge asymmetry measurement is

important for collider $W$-mass measurements because it reduces the mass uncertainties from parton distribution functions [20].

The Drell-Yan ($e^+e^-, \mu^+\mu^-$) production cross section measurement, $d^2\sigma/dMdy(|y| < 1)$, spans $11 < M < 500$ GeV/c$^2$ ($0.006 < x < 0.28$). It is in good agreement with the shape from NLO QCD calculations using recent parton distribution functions. However, precision comparisons of absolute levels await refinements of the luminosity measurement. The low mass analysis is still in progress, so there will be updated results to come.

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